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Solar System Exploration Augmented by In Situ Resource Utilization: System Analyses, Vehicles, and Moon Bases for Saturn Exploration

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Abstract

Human and robotic missions to Saturn are presented and analyzed with a range of propulsion options. Historical studies of space exploration, planetary spacecraft and astronomy, in situ resource utilization (ISRU), and industrialization all point to the vastness of natural resources in the solar system. Advanced propulsion is benefitted from these resources in many ways. While advanced propulsion systems were proposed in these historical studies, further investigation of nuclear options using high-power nuclear electric and nuclear pulse propulsion as well as advanced chemical propulsion can significantly enhance these scenarios. Updated analyses based on these historical visions are presented. At Saturn, nuclear pulse propulsion with alternate propellant feed systems and Saturn moon exploration with chemical propulsion and nuclear electric propulsion options are discussed. Issues with using in situ resource utilization on Saturn's moons are discussed. At Saturn, the best locations for exploration and the use of the moons as central locations for Saturn moon exploration are assessed. Environmental issues on Titan's surface may present extreme challenges for some ISRU processes. In-space bases for moon-orbiting propellant processing and ground-based processing will be assessed.

Keywords: in situ resource utilization (ISRU), moon base, rocket propulsion, systems analysis, specific impulse, nuclear propulsion

1. Introduction

Exploration and utilization of the outer solar system have always been a goal of the planetary science community and spacecraft engineers. Saturn with its fantastic ring system and many diverse moons has been the focus of exploration by the two Voyager flyby missions and the orbiting Cassini spacecraft. These space vehicles have identified areas of great scientific interest and also places on the moons where water, cryogenic ices, and other natural resources can be gathered. Using in situ resource utilization (ISRU) will allow more extensive exploration of the planet and its moons. This chapter presents analyses of the transportation options in the Saturn system, such as nuclear electric orbital transfer vehicles and chemical propulsion

moon landers. Far future human exploration, using nuclear propulsion is also addressed. A combination of these technologies may allow excellent surveys of the moons and then finally human exploration and perhaps moon base construction.

2. In situ resource utilization (ISRU)

In situ resource utilization (ISRU) is the use of materials on other bodies in the solar system. These in situ materials can be in the regolith, the atmosphere, or any other part of the natural environment. Using ISRU on or in the vicinity of many planetary bodies has been studied for decades. Numerous experiments have been conducted to define the methods of extracting resources from ices, gases, and regolith. Some of the earliest ISRU experiments were conducted in 1965 [1]. Based on spectroscopic measurements from Earth, simulated lunar rock and dust were created. The simulated rock and dust were then subjected to chemical processes that were designed to extract oxygen from the lunar materials [1]. Mars ISRU has been addressed in numerous references [2–6]. Reference [6] (JSC) discusses the six steps in ISRU development: identification, prospecting, resource capturing, utilization (propellants, etc.), power generation, and manufacturing. Additional extensive experiments and analyses are planned for the Mars 2020 rover, with an experiment called MOXIE that will separate oxygen from Mars' carbon dioxide atmosphere [7]. A concerted effort of many organizations, the commercial lunar propellant architecture, was focused on the efforts to capture lunar polar ice [8]. Using ISRU on outer planet moons was addressed in Refs. [9, 10] (HOPE, Ash, and BP). Outer planet analyses for capturing fusion fuels from Uranus and Neptune were conducted in Refs. [11–13].

3. Saturn and its moons

Saturn is the second largest planet in the solar system. Its orbit has an average distance from the Sun of 1.433 billion km. The ring system surrounding Saturn is very extensive and spectacular and has a rich set of resonances and dynamics. The Cassini mission spacecraft instruments gathered a rich set of data throughout its lifetime. Saturn also has powerful radiation belts both near the planet and far beyond the ring system. Due to the radiation environment, the moons are a more important location for any spaceflight operations.

Based on the observations of the Voyager and Cassini spacecraft, the moons of Saturn contain a rich set of ices. Spectroscopic data show the nature of these ices to be water ice with other frozen gases: nitrogen, methane, etc. The moons' temperatures are in the range on 75–130 K. **Table 1** provides the density of the major moons. The relatively low density also implies that the moons are primarily composed of frozen ices.

Figure 1 shows the semimajor axes of the moon. Iapetus is the most distant at 3.56 billion km from Saturn. The most proximate major moon is Mimas, which is only 185,000 km from Saturn [14–19]. Additional references on the moons of Saturn are provided at the end of this chapter [20–30].

3.1 Enceladus

Enceladus is a small icy moon near the outermost ring of Saturn; its radius is 248 km. Its semimajor axis is 238,020 km. Its gravity level is 2×10^{-2} of Earth's gravity. This moon is particularly exciting as it is sewing water into space, and its water

Moon	radius (km)	mass (10 ²⁰ kg)	density (kg/m ³)
Mimas	191.0	0.38	1,152.0
Enceladus	248.0	1.08	1,606.0
Tethys	526.0	6.18	956.0
Dione	560.0	10.96	1,470.0
Rhea	762.0	23.10	1,234.0
Titan	2,575.0	1,345.50	1,880.0
Iapetus	712.0	18.10	1,088.0

Table 1.
Saturn moon density, modified from Ref. [14].

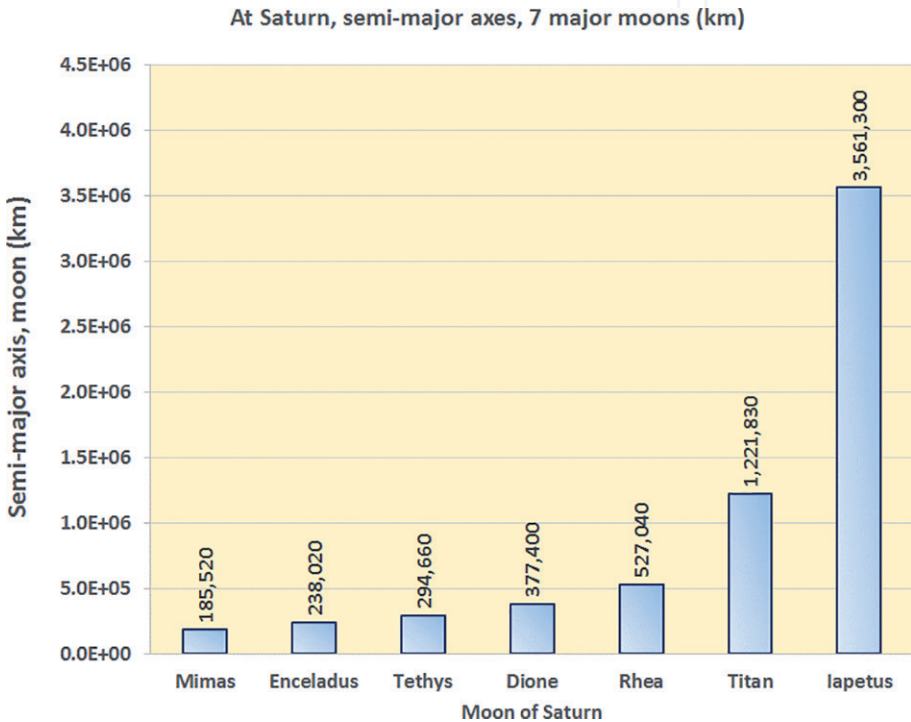


Figure 1.
Semimajor axes of the seven major moons of Saturn.

is feeding mass to Saturn’s rings. The water plume emanates from the so-called tiger stripes in the southern hemisphere. The temperature of the tiger stripes is 10–100°K warmer than the surrounding icy surface. The Cassini spacecraft had made multiple flybys of Enceladus and detected organic molecules in the water plume. Thus, this moon may harbor the precursors of simple life forms.

3.2 Titan

Titan is the largest moon of Saturn with a radius of 2576 km. Its semimajor axis is 1.2218 million km. Titan has an appreciable atmosphere of 98.4% nitrogen, 1.4% methane, and other trace gases. Its gravity is 0.14 of Earth’s gravity. Because of its dense clouds, radar must be used to gather data from space. The Cassini spacecraft observed lakes on Titan; these lakes are composed of liquid methane and ethane. These lakes are approximately that size of the Great Lakes of North America. The surface of Titan is approximately 94°K, and the surface is a complex crust of water ices and frozen hydrocarbons. Simulations and gravity data suggest an ocean of liquid water about 100 km below the frozen surface.

Body	R (km)	m (kg)	a (m/s^2)	G level
Saturn	60,268.0	5.6800E+26	1.0434E+01	1.066E+00
Mimas	191.0	3.7900E+19	6.9321E-02	7.079E-03
Enceladus	248.0	1.0800E+20	1.1717E-01	1.197E-02
Tethys	526.0	6.18E+20	1.4904E-01	1.522E-02
Dione	560.0	1.1000E+21	2.3405E-01	2.390E-02
Rhea	762.0	2.3100E+21	2.6546E-01	2.711E-02
Titan	2,575.0	1.3455E+23	1.3540E+00	1.383E-01
Iapetus	712.0	1.8100E+21	2.3824E-01	2.433E-02

Table 2.
Gravity levels of Saturn and its major moons.

3.3 Iapetus

Iapetus is one of the most distant large moons from Saturn, and its radius is 712 km. Its gravity level is 2.4×10^{-2} of Earth’s gravity. This moon has a ridge that girdles a significant fraction of the equator. One hemisphere has very dark material, with an albedo is 2–6%, while the other hemisphere in comparison is very bright. The composition of the dark material is perhaps organic material and carbon. Simulations have suggested that the dark materials may have been deposited by numerous particle collisions. An alternative theory is that magma from the interior has risen to the surface and that magma may be visible in photos as materials that have filled in numerous craters.

3.4 Icy moon gravity levels

Table 2 provides the gravity levels of the major moons. While Titan has a surface gravity level of 14% of Earth, the remaining moons have gravity levels of 1×10^{-2} Earth gravity or less. Such low gravity levels may make transportation, operations, and industrial processing on the moon’s surfaces very challenging. On the other hand, the low gravity is helpful in reducing the delta-V needed to transport large masses to and from the moon’s surface.

4. Mission planning and delta-V data

Table 3 provides the delta-V to reach low orbit about the moon and the moon’s escape velocities. As Titan is the largest moon, the delta-V for escape is the largest: 3.17 km per second. These delta-V values will be important in selecting the most attractive moons for ISRU processing. The planetary gravitational constants and radii were found in Ref. [19].

4.1 Exploration vehicles

As a prelude to human missions, a detailed survey of the major Saturnian moons is planned. The survey is driven by ISRU requirements: identification, prospecting, resource capturing, and utilization. The final steps will be power generation and manufacturing on the surface of the moons.

A first survey of the major moons will include orbiters and small landers. A suggested set of spacecraft would be nuclear electric propulsion transfer vehicle and a small chemical propulsion lander. The NEP transfer vehicle would use a complement

Body	G (km ³ /s ²)	R (km)	r, or altitude (km)	Estimated landing or ascent delta-V (km/s), with 20% gravity losses	Escape velocity (km/s), with 20% gravity losses
Saturn	3.7931E+07	60,268.0	10	30.102	42.575
Mimas	2.5290E+00	191.0	100	0.112	0.195
Enceladus	7.2065E+00	248.0	100	0.173	0.289
Tethys	4.1237E+01	526.0	100	0.308	0.475
Dione	7.3400E+01	560.0	100	0.400	0.614
Rhea	1.5414E+02	762.0	100	0.507	0.763
Titan	8.9781E+03	2,575.0	100	2.198	3.169
Iapetus	1.2078E+02	712.0	100	0.463	0.699

Table 3.
Landing, launch, and escape of delta-V for the seven major moons of Saturn.

of science instruments to assess the ices and regolith on the moons’ surface. A mega-watt class radar system aboard the orbiter would provide data on ice thicknesses and regolith composition. Once an attractive site is identified, the chemical propulsion lander can descend to the surface and perform a series of in situ assessments. Chemical laboratories delivered to the surface can sample the ices and regolith. Samples may even be returned to orbit for caching and planned return to Earth.

4.2 Space vehicle sizing

The nuclear electric propulsion (NEP) vehicles or orbital transfer vehicles (OTVs) are described by the following mass scaling equation. The dry mass scaling equation used was [31–35]

$$M_{\text{dry, stage}} \text{ (kg)} = \text{reactor specific mass (kg/kW)} \cdot P \text{ (kWe)} + 0.05 \cdot M_p \text{ (kg)} + \text{fixed mass (kg)}$$

The low-thrust OTV delta-V values are noted in **Tables 4** and **5** for each round-trip mission.

The NEP vehicle has a specific impulse of 5000 seconds with a propulsion system efficiency of 50%. The power level of the reactor was 10 MWe, and the reactor specific mass was 10 kg/kWe. The propellant tankage dry mass fraction was 5%, and the fixed mass was 20 MT [31]. Additional mission assumptions are discussed in the next sections.

The chemically propelled oxygen/hydrogen propulsion landers were described with a mass scaling equation. In sizing the chemical propulsion landers, a vehicle mass scaling equation was used [31–35]:

$$M_{\text{dry, stage}} \text{ (kg)} = M_{\text{dry, coefficient}} \cdot M_p \text{ (kg)}$$

where $M_{\text{dry, stage}}$ is the stage dry mass, including residual propellant (kg); $M_{\text{dry, coefficient}}$ is the B mass coefficient (kg of tank mass/kg of usable propellant mass); M_p is the usable propellant mass (kg).

In almost every case, the chemical propulsion landers had a B coefficient of 0.4. With the very large delta-V missions at Titan, the B coefficient was 0.2. The lander specific impulse was 480 seconds [31, 36–38].

Moon	Mimas	Enceladus	Tethys	Dione	Rhea	Titan	Iapetus	Total
Mimas	0.000	3.530	5.903	8.594	11.639	17.443	22.584	69.694
Enceladus	3.530	0.000	2.829	5.191	8.273	14.088	19.391	53.303
Tethys	5.903	2.829	0.000	2.848	5.775	11.554	16.699	45.608
Dione	8.594	5.191	2.848	0.000	3.084	8.897	14.261	42.876
Rhea	11.639	8.273	5.775	3.084	0.000	5.817	11.210	45.797
Titan	17.443	14.088	11.554	8.897	5.817	0.000	5.693	63.491
Iapetus	22.584	19.391	16.699	14.261	11.210	5.693	0.000	89.837
	69.694	53.303	45.608	42.876	45.798	63.491	89.837	

Table 4.
Round-trip delta-V map for Saturn’s moons (seven moons).

Moon	Mimas	Enceladus	Tethys	Dione	Rhea	Titan	Total
Mimas	0.000	3.530	5.903	8.594	11.639	17.443	47.110
Enceladus	3.530	0.000	2.829	5.191	8.273	14.088	33.911
Tethys	5.903	2.829	0.000	2.848	5.775	11.554	28.909
Dione	8.594	5.191	2.848	0.000	3.084	8.897	28.615
Rhea	11.639	8.273	5.775	3.084	0.000	5.817	34.588
Titan	17.443	14.088	11.554	8.897	5.817	0.000	57.798
Total	47.110	33.911	28.909	28.615	34.588	57.799	

Table 5.
Round-trip delta-V map for Saturn’s moons (six moons, without Iapetus).

4.3 Mission delta-V results

Examples of the chemical propulsion lander masses are shown in **Figures 2** and **3**: Titan and Enceladus, respectively. At Titan and Enceladus, the smallest 1 MT payload landers would be for ISRU prospecting and exploration. The 50 MT payload landers would be for industrial scale ISRU propellant production plant delivery.

The NEP vehicle delta-V values are shown in **Tables 4** and **5**. The delta-V was computed with a low-thrust trajectory estimation algorithm. **Table 4** shows the round-trip delta-V values for trips between the seven major moons; the table shows that using Dione as a central exploration moon, the total delta-V for a fleet of OTVs is minimized. An option with only six moons was also investigated, noted in **Table 5**. As Iapetus is the most distant moon in the system of moons, a separate analysis was conducted excluding Iapetus. For both the seven moon and the six moon options of **Tables 4** and **5**, the moon Dione shows the minimal fleet delta-V. Though this is the moon showing the minimal delta-V for the entire fleet, the influence of the OTV and lander mass may change the optimal (or minimal mass) solution.

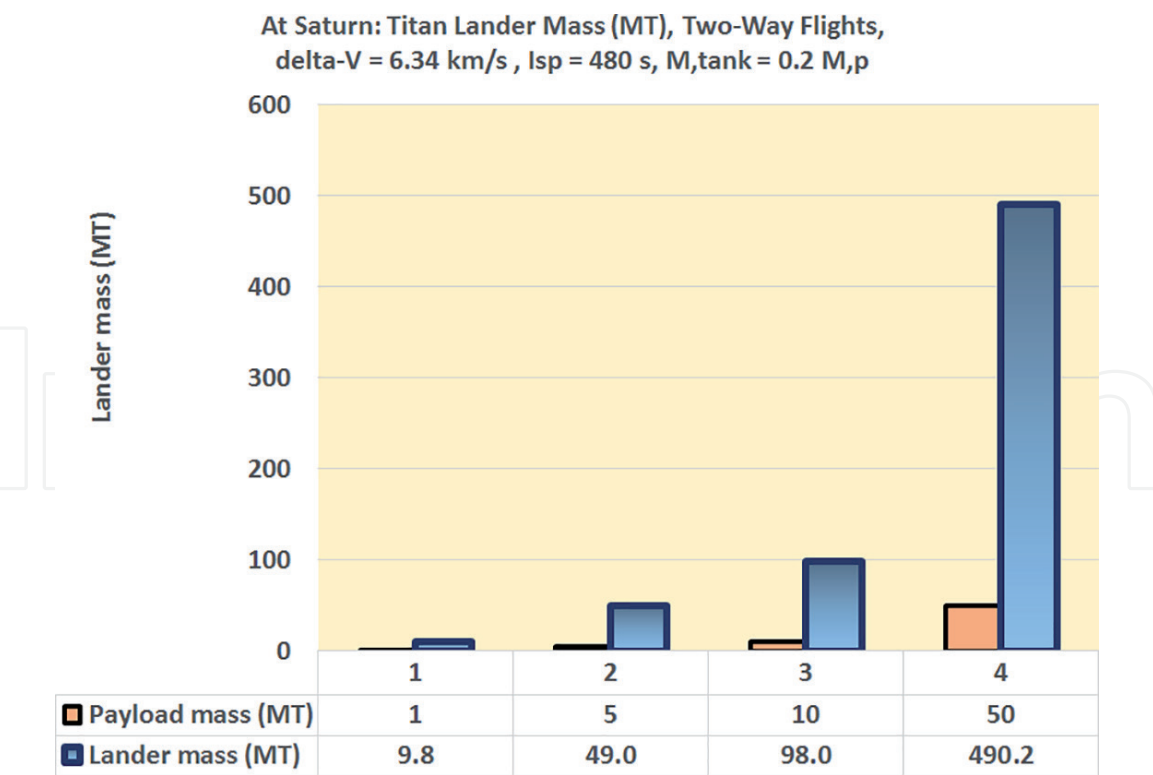


Figure 2.
Saturn moon lander mass for Titan, round-trip flights, payload masses of 1–50 MT.

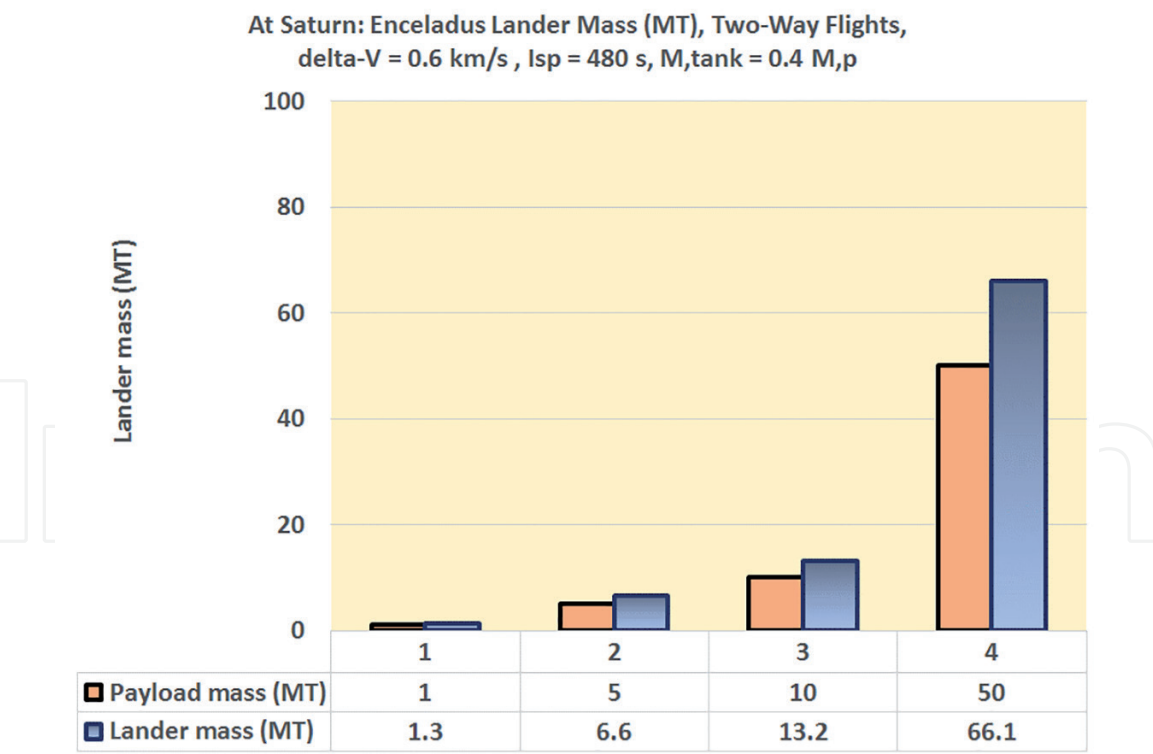


Figure 3.
Saturn moon lander mass for Enceladus, round-trip flights, payload masses of 1–50 MT.

4.4 Factory analysis

The ISRU factory will allow the OTV to be refueled from water ices on the moons. Initially, the OTVs, their science landers, and factory lander are delivered to the centric moon. The OTVs are delivered with no NEP propellants and only

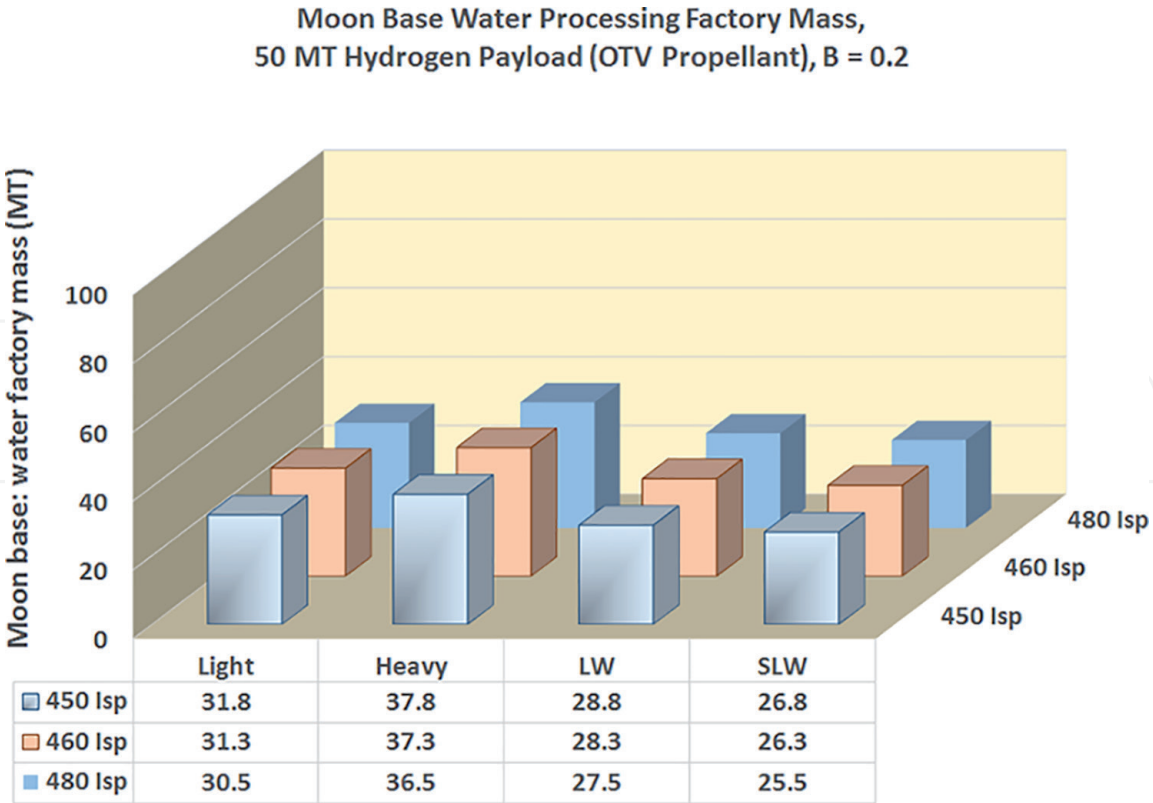


Figure 4.
Moon base factory masses, for 50 MT payload landers.

oxygen and hydrogen propellants for the science landers (with a 1 MT payloads) and 50 MT payload factory lander. Once in orbit about the centric moon, the factory lander with the 50 MT ISRU factory lands. The mining and conversion of water ice to oxygen and hydrogen for the factory lander’s ascent to orbit are conducted. Additional hydrogen is created on the centric moon and that hydrogen is delivered to the orbiting OTVs. The OTVs can then be dispatched on their moon exploration flights to the other remaining moons. The factory lander will have to perform several flights to deliver the full propellant loads for the orbiting OTVs. **Figure 4** presents the estimated masses of a series of propellant factories. The factory masses are based on the lander Isp and the factory design, which is a function of the level of integration with the lander.

For example, a light propellant factory has separate tanks for lander and factory. A heavy propellant factory has separate tanks for lander and factory but has higher masses for enclosures that protect against the elements, winds, micrometeoroids, etc. Also, higher masses are included for foundations for cryogenic surfaces (creating a stable structure for the base). For a super lightweight propellant factory, propellants and all fluids are fed to and stored in lander tanks. Appendix A delineates the masses in the heavy configuration.

In **Figure 5**, the masses of the ISRU factory and the OTV propellant masses needed for the Saturn moon survey are compared. With the cases without Iapetus, six moons are surveyed. The mass of the ISRU factory is 50 MT. In all cases, the total OTV propellant load is significantly higher than the factory mass. Thus, the use of the factory can enable not only the first survey of the moons but many more. Typically, nuclear reactors have been designed for a 7-year life at full power and a 10-year overall life (operating for the last 3 years at a reduced power level). Given the typical 7-year lifetime of a space nuclear reactor [13], the number of OTV flights can be 6–7.

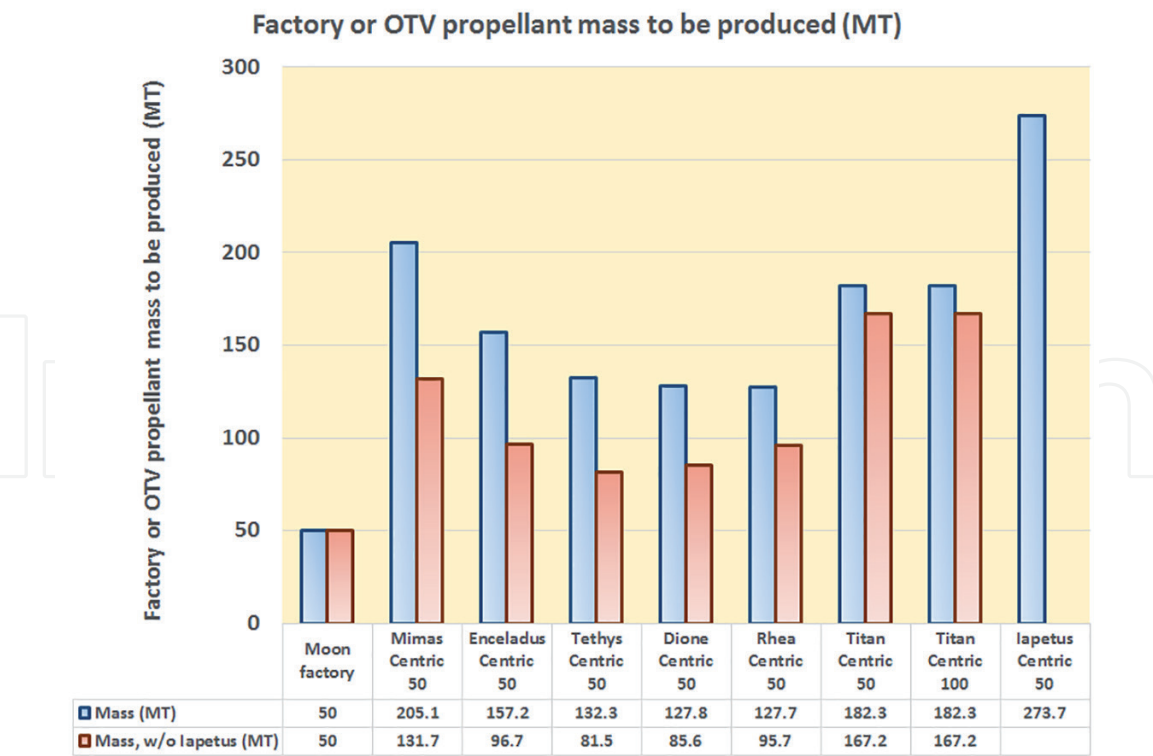


Figure 5.
Moon factory mass comparison with OTV propellants needed.

4.5 Mission scenario results and interpretations

To fully explore the moons, a fleet of OTVs and landers were conceived. One OTV and one lander would visit each moon. At the central or centric moon, a 50 MT ISRU factory is landed. The 50 MT payload includes an ISRU factory and a set of empty propellant tanks. The factory creates the propellant for all of the NEP OTVs and landers. The propellant tanks will be filled with the moon-derived ISRU propellants.

The lander was designed to bring that propellant into orbit to refuel the OTVs. The lander propellant tanks are fueled with oxygen and hydrogen. The lander then ascends to the escape conditions of the moon’s orbit. Then the lander performs a rendezvous with the OTV(s) and refuels OTV(s); it may also refuel the smaller exploration landers aboard the OTV(s). The newly fueled OTV with its exploration lander completes the orbit transfer to another moon. After completing its exploration, the OTV returns to the moon with ISRU propellant factory.

An additional case for Titan with a 100 MT lander payload was included. This case was added as the lander delta-V for Titan is the highest of all of the moons; therefore, a larger propellant mass is needed for each flight. A larger lander payload case might be attractive in reducing the number of flights needed for refueling the OTVs.

An overall fleet mass of the OTVs and the landers was then estimated. The fleet consisted of one NEP OTV and lander designed to visit a specific moon. Each OTV carried a lander with a 1 MT payload. For the seven moon options, seven OTVs and seven exploration landers were sized. Each OTV was sized to operate from a central moon. As noted above, an additional lander operating from the centric moon was added to provide the ISRU refueling capability for the OTV fleet.

Using the mission delta-V values and vehicle sizing data, the following optima for moon exploration were found. In **Table 6**, the total mass of the OTV

Moon	OTV Mp (MT)	Lander (MT)	Mp Lander and Total OTV dry mass (MT)	mass
Mimas Centric 50	205.1	5.1	832.7	1,042.9
Enceladus Centric 50	157.2	9.7	811.9	978.9
Tethys Centric 50	132.3	14.4	814.8	961.4
Dione Centric 50	127.8	20.0	810.0	957.8
Rhea Centric 50	127.7	26.6	818.2	972.5
Titan Centric 50	182.3	362.6	876.0	1,420.9
Titan Centric 100	182.3	725.3	1003.5	1,911.1
Iapetus Centric 50	273.7	23.5	825.3	1,122.5

Table 6. Total masses of the lander and OTV fleets, for moon-centric options, including seven moons.

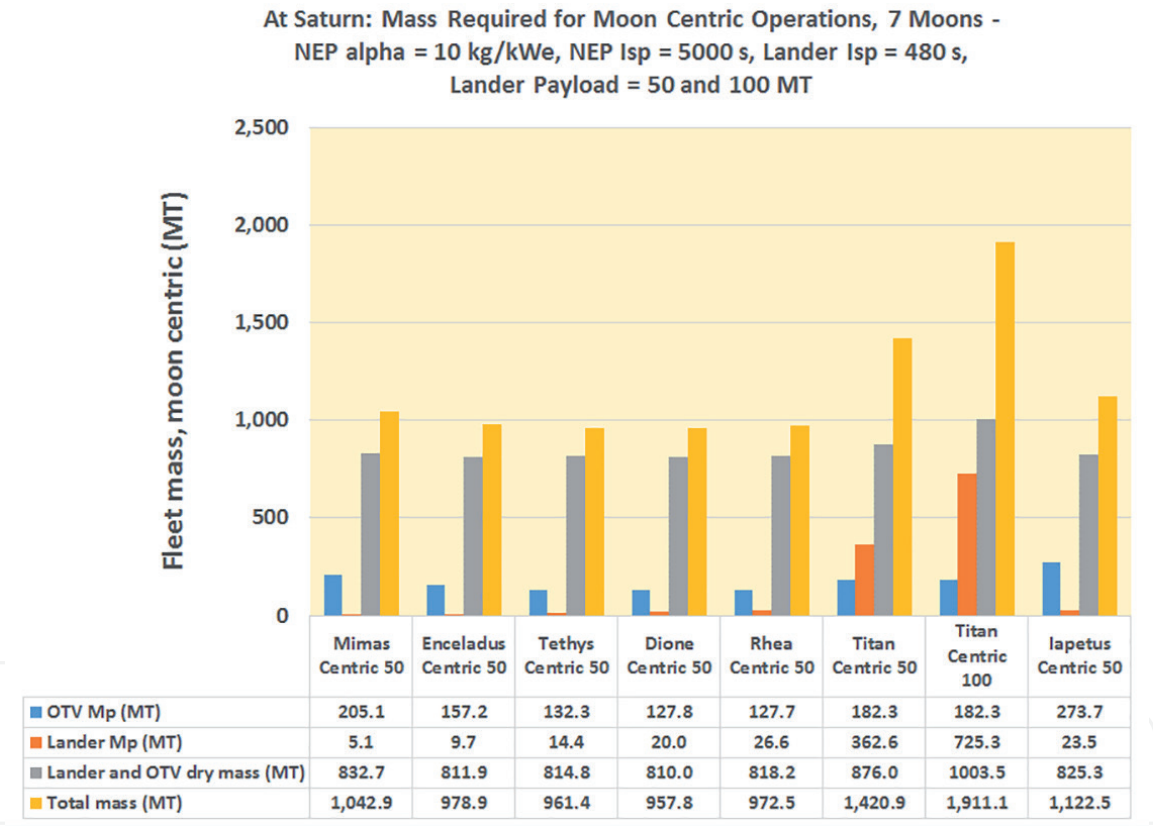


Figure 6. Total masses of the lander and OTV fleets, for moon-centric options, including seven moons.

and lander fleets using a central moon are shown; the minimal mass is 958 MT for the moon Dione. **Figure 6** also presents the fleet mass data. While Dione represents the minimal fleet mass, the optimum is fairly broad over a set of four moons: Enceladus, Tethys, Dione, and Rhea. After further exploration and consideration of currently imprecisely known factors (ice composition, regolith strength, ease of access to any subsurface moon oceans, etc.), an optimal moon can be selected.

Table 7 presents the same analyses, excluding Iapetus. In **Table 6**, the minimal fleet mass is found for the moon Dione. In **Table 7**, the minimal fleet mass is for the moon Tethys: the fleet mass is 785 MT. While Tethys represents the moon

Moon	OTV (MT)	Mp Lander (MT)	Mp Lander and OTV dry mass (MT)	Total mass (MT)
Mimas Centric 50	131.7	5.1	706.1	842.9
Enceladus Centric 50	96.7	9.7	685.9	792.4
Tethys Centric 50	81.5	14.4	689.2	785.2
Dione Centric 50	85.6	30.1	684.9	800.5
Rhea Centric 50	95.7	26.6	694.6	816.9
Titan Centric 50	167.2	362.6	752.3	1,282.1
Titan Centric 100	167.2	725.3	879.7	1,772.2

Table 7.
Total masses of the lander and OTV fleets, for moon-centric options, including six moons (without Iapetus).

with the minimal fleet mass, the optimum is fairly broad over a set of four moons: Enceladus, Tethys, Dione, and Rhea.

By excluding Iapetus, the total fleet mass is significantly reduced; for Dione, the fleet mass is reduced from 958 to 800 MT. Further restrictions of the moon exploration fleet (e.g., from six to four moons) may be needed to fit within the payload capacity of future interplanetary transfer vehicle (ITVs). As Iapetus is more remote than the other moons, it is possible that a separate ISRU space base may be more attractive than a centralized ISRU space base.

Due to the low gravity level of the moons, a moon-orbiting space base may be attractive. Processing control of ices in a low-gravity environment may be very difficult. It is suggested that an artificial gravity space base in orbit about the moon may be the best location of resource processing. After a series of small missions have been conducted, a large ISRU space base may be established. The base might be a refueling point for extensive exploration. The water ices from the moons would be brought to the space base for processing, to allow the refueling of the landers and the NEP OTVs.

5. The far future: human Saturn missions with nuclear pulse propulsion (NPP)

Historical analyses of human missions to the outer planets have included many nuclear propulsion conceptual designs. Nuclear pulse propulsion was investigated and was considered a practical alternative to any chemical propulsion options. The round-trip impulsive delta-V for such missions was approximately 60 km/s [34, 38–41].

Human missions to Jupiter and Saturn were suggested in the 1960s. Large-scale exploration missions with many astronauts were planned. The primary propulsion system considered was nuclear pulse propulsion. Many small nuclear packages were exploded behind the vehicle, propelling it onto a high-thrust trajectory. For a human Jupiter or Saturn mission, the delta-V was approximately 60 km/s. While the round-trip Jupiter missions were designed to orbit Callisto, at Saturn, Titan was selected. Titan is the largest moon of Saturn, the delta-V to land there is high, 2.2 km/s, and the escape velocity is 3.17 km/s. These values represent an all propulsive landing on Titan and include a 20% delta-V penalty for gravity losses [23]. Such a propulsive delta-V was selected to make the comparisons with the other

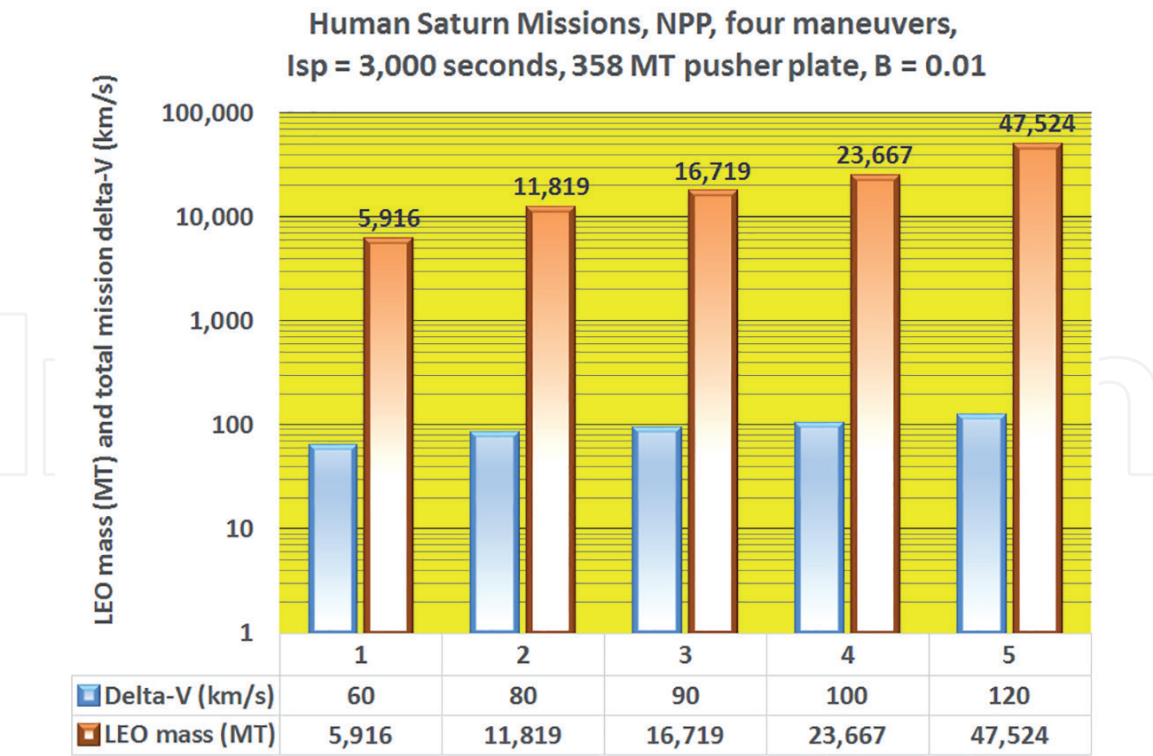


Figure 7.
Saturn NPP sizing and mission data, B = 0.01 Mp [23].

moon landers as consistent as possible. If a lander were to be used for many flights, repacking parachutes or reoutfitting a robotic lander with additional parachutes on orbit may be cumbersome.

Figure 7 shows the mass of the Saturn missions for a range of delta-V of 60–120 km/s. While the 60 km/s missions represent a fast mission to Saturn (approximately 250–500 days), a fast mission in both directions may require 120 km/s. The vehicle mass for the 120 km/s missions is over 47,000 MT, while the 60 km/s mission requires less than 6000 MT.

In Ref. [23], using ISRU for refueling a fast Saturn mission was analyzed. Saturn’s atmosphere was considered a likely source of the nuclear fuels: helium 3 and deuterium. After analyses of the ISRU transportation systems, it was found that Uranus was a more likely atmospheric fuel source. The complexity of moving OTVs from low Saturn orbit to an assembly point (such a Titan) and the trip time for the low-thrust transfers (for a round-trip delta-V of over 94 km/s) were very prohibitive. With the Uranus option, the nuclear fuels were mining and sent to Titan. The round-trip OTV delta-V for lifting the mined fuels to a moon of Uranus was approximately 32 km/s. While the delta-V for mining transportation is lower, the need for an interplanetary transfer vehicle (ITV) is apparent. A relatively low-energy Uranus to Saturn transfer is possible with an NEP ITV. While the ISRU option for the fast Saturn mission is attractive, the time for gathering the nuclear fuels may require 10 years of mining operations.

6. Concluding remarks

Saturn and its moon have always been fascinating. Ever since Galileo Galilei noted in his early telescopic observations that “Saturn has ears,” the excitement

for Saturn exploration has been strong. Both Saturn and its moons are rich with resources: hydrogen and helium in the planet's atmosphere and ices on the moons. Using the resources of the outer planet moons, new options for exploration are possible. Multiple moons can be visited and explored. High-power OTV with nuclear power can reveal the nature of the ices and regolith of the moons.

Detailed exploration of the major moons can be completed with a set of small chemical propulsion moon landers and nuclear electric orbital transfer vehicles. A series of such OTV and landers showed several optimal locations for conducting a moon survey. Dione was an optimal location for the minimization of the OTV and lander fleet mass. A central moon location allowed a large ISRU factory to fuel many OTV and exploration lander flights.

Far future human exploration of the Saturn system may employ very high-energy nuclear propulsion systems. Nuclear pulse propulsion vehicles may allow fast transfers to Saturn and the delivery of robotic exploration vehicles and human explorers. Using ISRU for refueling a fast Saturn mission was analyzed. Saturn's atmosphere was considered a likely source of nuclear fuels: helium 3 and deuterium. After analyses of the ISRU transportation systems, it was found that Uranus was a more likely atmospheric fuel source. There are numerous benefits of ISRU in Saturn and Uranus systems. With ISRU, our exploration options are nearly endless, and the abilities to uncover the secrets of Saturn moons are awaiting our scientific investments.

Nomenclature

3He	helium 3
4He	helium (or helium 4)
AMOSS	atmospheric mining in the outer solar system
ASC	aerospacecraft
CC	closed cycle
delta-V	change in velocity (km/s)
GCR	gas core rocket
GTOW	gross takeoff weight
H ₂	hydrogen
He	helium 4
ISRU	in situ resource utilization
Isp	specific impulse (s)
K	kelvin
kWe	kilowatts of electric power
LEO	low Earth orbit
MT	metric tons
MWe	megawatt electric (power level)
NEP	nuclear electric propulsion
NPP	nuclear pulse propulsion
NTP	nuclear thermal propulsion
NTR	nuclear thermal rocket
OC	open cycle
O ₂	oxygen
PPB	parts per billion
PSC	permanently shadowed craters
PSR	permanently shadowed regions

A. Appendix A: moon base factory masses

Propellant factory for moons: The factory will take the raw materials from the outer planet moon's surface, lake(s), or ocean(s) and process them into oxygen and hydrogen for the chemical propulsion lander(s). Additional liquid hydrogen will also be produced as the fuel for the NEP OTVs (hydrogen MPD or PIT propulsion). Water may have to be processed from regolith or and liquid reservoir (lake(s), or ocean(s)).	450		460		480	
	Lander MP		Lander MP		Lander MP	
	B		B		B	
Heavy Propellant factory. Mass, estimated (MT)	0.2		0.2		0.2	
	Mp (MT)		Mp (MT)		Mp (MT)	
	H2 mass (MT)		H2 mass (MT)		H2 mass (MT)	
Subsystem list - overview:	26.33		25.58		24.22	
Factory machines.	2		2		2	
Enclosures, protection against the elements, winds, micrometeoroids, etc.	2		2		2	
Foundations for cryogenic surfaces (creating a stable structure for the base).	0		0		0	
Buoyancy systems, if floating on cryogenic lakes, oceans, etc.	0		0		0	
Safety systems.	1		1		1	
Drilling systems (potentially deep drilling, for salt water oceans).	0		0		0	
Melting – heating systems (for permafrost, cryogenic ices, extracting water from water ice-regolith mix, etc.).	2		2		2	
Liquid feed systems.	1		5.27		5.12	
Gaseous feed systems.	1		1		1	
Liquefaction systems.	2		2		2	
Liquid storage: cryogenic.	2		5.27		5.12	
Liquid storage: non-cryogenic.	2		2		2	
Gaseous storage.	2		2		2	
And:						
Liquid oxygen and liquid hydrogen storage.	1		5.27		5.12	
Liquid oxygen and liquid hydrogen transfer to landers.	1		1		1	
And:						
Liquid hydrogen - Payload transportation to landers.	1		1		1	
Liquid hydrogen - Payload loading onto landers.	1		1		1	
Subtotal (MT)	21		32.80		31.53	
Total (MT), factory and payload storage	37.80		37.35		36.53	



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